# DEMONSTRATION OF TWO-WAY EXTREMELY HIGH FREQUENCY (EHF) SATELLITE COMMUNICATION (SATCOM) USING SUBMARINE-SURVIVABLE PHASED ARRAYS

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## ABSTRACT

*U.S. submarines are faced with the challenging dilemma of addressing the need for higher data rate satellite communications (SATCOM) without significantly increasing the size of the SATCOM antenna. The planar form factor of phased array technology, along with the ability to steer beams electronically, has led to submarine antenna concepts that can simultaneously improve performance, utilize the submarine sail volume more efficiently, and minimize the impact to platform stealth. Through technology development under the Office of Naval Research (ONR), submarine-survivable phased arrays that address EHF SATCOM have been fabricated, tested, and delivered to the Navy by Boeing Phantom Works.*

*The Naval Undersea Warfare Center has recently performed notional system integration and testing of these arrays. Q-band (44 GHz) uplink- and K-band (20 GHz) downlink-phased array antennas were tested successfully using both the Military Strategic and Tactical Relay (MILSTAR) and Ultra High Frequency Follow-On (UFO) military satellites. The antennas were integrated with the Raytheon Follow-On Terminal (FOT) for full-duplex SATCOM testing. Full-duplex data rates of up to 64 kbps were attained using the phased arrays under optimal weather conditions. Bit error rate testing (BERT) was performed with no bit errors recorded. Initial tests were performed with the phased arrays mounted on a stationary platform; subsequent testing involved integration of the phased arrays into a notional housing atop a submarine mast. Notional mast testing included simulated ship motion using a six-axis motion table that is located on the roof of the Naval Undersea Warfare Center Division Newport's (NUWCDIVNPT) Building 68 (B-68) with support from the Submarine EHF Satellite Communication Integration Facility (SESIF).*

*Half-duplex testing was also performed using a fiber optic (FO) link to carry both the control and radio frequency (RF) signals for the downlink-phased array on a single FO cable. This paper will provide an overview of the array technology and will describe the configurations and results of SATCOM testing.*

## INTRODUCTION

U.S. submarines are required to communicate with shore commands using the existing military SATCOM infrastructure and the OE-562 mast-mounted reflector antenna. The volume available on submarines to support any mast-mounted antenna is limited; and that imposed volume constrains the size of the aperture that can be accommodated, which, in turn, restricts the antenna gain and supportable data rates. The area of the aperture that can be fielded within the available volume is further limited by the essential capabilities of mechanically steering the reflector in any direction as well as protecting the antenna from the harsh submarine environment.

Submarine-survivable phased array technology provides an opportunity to increase performance—per unit volume—for highly directive SATCOM antennas. A planar antenna that is electronically steerable can be configured on a submarine mast such that only azimuth rotation is required. To minimize overall volume requirements, the radome can be embedded within the array, achieving a configuration of phased array apertures onto a submarine mast that is larger than the largest reflector antenna configured for the same sail bay volume. For this reason ONR and NUWC have been investigating the feasibility of submarine-survivable phased arrays while concurrently addressing military SATCOM frequency bands.

This paper addresses the construction of the phased arrays and the evolution of the over-the-air testing from K-Band (Half Duplex) to K and Q-Band (Full Duplex). The testing was conducted first under static conditions, then under simulated ship's motion on the six axis motion table. After the satellite link testing was debugged, further system improvements using FO links for RF and support signals were evaluated.

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## PHASED ARRAY DETAILS

A submarine-survivable receive-only phased array antenna operating at K-band was developed by Boeing Phantom Works under ONR investment and delivered to the Navy in 2001. The array supports both right-hand and left-hand circular polarization (switchable) and consists of 508 elements. The overall array structure is approximately 17 inches (”) in diameter and 2.7” deep. The active aperture is approximately 4.7” x 4.2”, as shown in figure 1. The array was tested to verify electrical operation, then subjected to hydrostatic-pressure testing, and re-evaluated. The array survived pressure testing with no noticeable change in performance.

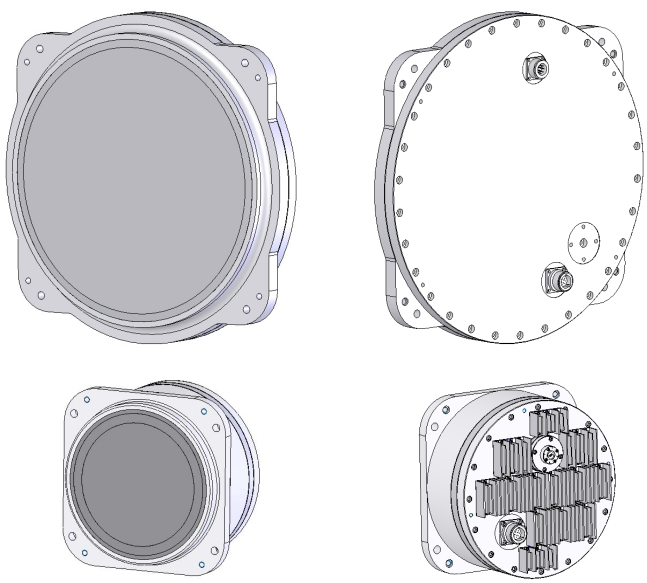

Figure 1: (U) Boeing K-band Rx Phased Array (top) & Boeing Q-band Tx Phased Array (bottom)

Under a subsequent ONR-funded effort, a transmit-phased array operating at Q-band was designed and fabricated by Boeing. This array employed the same submarine-survivable mechanical design features as the K-band array. The Q-band array consists of 256 elements arranged in a triangular lattice. The aperture is rhombic in shape, measuring less than 2.3” on a side. The overall antenna structure is cylindrical, measuring approximately 11.25” in diameter and 7.125” deep, as shown in figure 1.

Both arrays utilize a system phased array controller (SPAC) that is used for pointing and steering the antenna beam. The SPAC then communicates with electronic beam steering controller boards, embedded in the array structure, that provide the final commands to the element phase shifters.

## HALF-DUPLEX TESTING

The half-duplex testing was initially performed in FY05 with the K-band downlink phased array antenna and conducted under two conditions: static and dynamic. The legacy low data rate (LDR) satellite terminal was used to establish a downlink with the MILSTAR satellite. At the beginning of each test session the phased array (while in a static condition) was manually peaked up on the satellite beam using a manual peak-beam search, while continuously monitoring the SNR of the downlink signal. The K-band phased array antenna does have integral functionality to find and lock on to the strongest signal in the sky, but the hopping nature of the MILSTAR signal precluded the use of this functionality. The pointing of the phased array for the dynamic motion table testing was accomplished via a personal computer (PC) controller (laptop computer) in an open-loop fashion using the motion table leg outputs with no integration with the satellite terminal, as shown in figure 2. The K-Band SPAC supplied with the phased array was used to process the RS232 pointing commands from the computer into the data protocol of the phased array. The SNR of the downlink was continuously monitored and recorded for both test conditions.

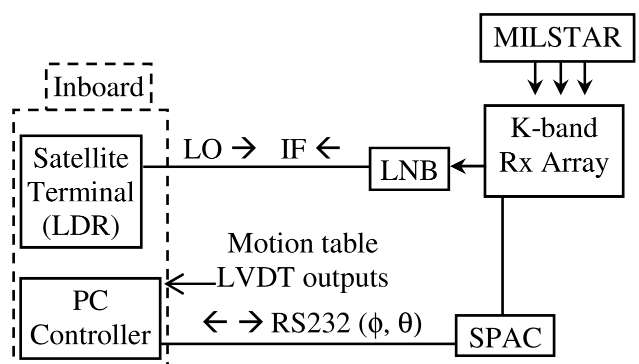


Figure 2: (U) Schematic of half-duplex dynamic motion table test setup

Testing was first performed in a static test condition. In order to initially establish the downlink, a Type 8 Mod 3 EHF periscope antenna was connected to the LDR terminal to provide the necessary “handshaking” to avoid terminal faults that would occur were no antenna connected to the terminal. The RF feed that would usually go to the Type 8 Mod 3 EHF periscope antenna was instead connected to the phased array; this arrangement enabled the downlink to be established using the phased array and its stand-alone pointing software. Development is currently underway to design an intermediary interface between the terminal and the phased arrays that will enable pointing of the phased arrays via the terminal and

will provide resolver motor feedback, thereby eliminating the need to leave the Type 8 Mod 3 periscope antenna connected.

For the dynamic test, the K-band downlink phased array was integrated into a notional wedge housing designed with ridged sides to reduce radar cross section (RCS). This notional housing was then mounted onto the Submarine Sensor Test Mast (SSTM) which was then base mounted to the six-axis motion table. Dynamic testing was performed under the following motion table profiles: profile B (± 5 degree [º] pitch, ± 10º roll), profile C (± 10º pitch, ± 20º roll), and profile E (± 5º pitch, ± 10º roll, with added heave).

The pointing for the dynamic test condition was established by first inputting the initial static pointing coordinates of the phased array into the LabView pointing software. The outputs from the linear variable differential transformers (LVDTs) on the motion table legs were also input into the pointing software. The pointing software contains a transformation matrix that uses superposition to take the initial pointing inputs as well as the LVDT outputs and transform them into appropriate spherical pointing values (phi and theta), which are then used to point the phased array beam. These commands are transmitted to the SPAC, via the RS232 bus, which, in turn, points the array. In this way the pointing method for the testing was open loop, as it did not involve any interfacing with (or feedback from) the LDR satellite terminal. During this testing (under all three motion table profiles [B, C, and E]) the reported SNR varied between 26 and 30 dB, indicating that the link was being dropped. Further pointing algorithm development improved this problem as seen in later testing.

Many lessons were learned during the half-duplex testing. The transformation matrix proved to be quite a challenge and the hopping nature of the MILSTAR signal was difficult to resolve in the RF architecture of the test setup. By working through these challenges the half-duplex testing paved the way for the FY07-FY08 full-duplex phased array testing. The half-duplex testing demonstrated the ability of the K-band narrowband phased array at Technical Readiness Level (TRL) 6: testing was performed using a Navy SATCOM terminal, functioning in a representative operational environment, while integrated into the SSTM while under motion on the six-axis motion table. The packaging of the K-band phased array at TRL 6 was demonstrated in a representative physical environment through hydrostatic pressure testing to 1000 psi, which simulated the submarine test environment. As described, in using the transformation matrix, the array control functions were operated independent of the SATCOM terminal (i.e., terminal integration of array pointing functions was not demonstrated in the initial half-duplex testing). Bit error rate testing was not performed for this initial half-duplex testing; the SNR of the downlink was, instead, monitored continuously. Bit error rate testing was included in later tests to better characterize the SATCOM link.

## FULL-DUPLEX TESTING OBJECTIVES

In light of the previous half-duplex testing performed, full-duplex testing was performed using both the K-band phased array antenna and a Q-band phased array antenna. The Q-band phased array represents a high-fidelity laboratory integration of components [TRL 5], utilizing submarine packaging similar to the K-band receive array (although not all hydrostatic-pressure-proof components were included in the final array assembly), and demonstrating acceptable gain and beam pattern by means of anechoic chamber tests. Full-duplex testing was performed with the following three primary objectives: a) to demonstrate the Q-band phased array at TRL 6, b) to demonstrate a full-duplex satellite link using only phased arrays, all within a relevant environment and integrated into the SSTM while under motion on the six-axis motion table, and c) to integrate the array pointing algorithm into the FOT satellite terminal (NOTE: This test stage provides only partial terminal integration).

In addition to proving the robustness of a full-duplex system employing only phased arrays, the objective of the full-duplex testing was to demonstrate the Q-band phased array's transmit capability to point and radiate a modulated, encrypted signal, supplied by a Navy-qualified submarine FOT and High Power Amplifier (HPA) system, toward a MILSTAR or UFO EHF satellite.

## FULL-DUPLEX STATIC TESTING

Full-duplex phased array testing was performed using the Q-band phased array for the uplink and the K-band phased array for the downlink. As with the half-duplex testing, the full-duplex testing was performed first in a static test condition, with subsequent dynamic testing performed with the arrays integrated into the SSTM and mounted on the six-axis motion table.

The test setup for the full-duplex static testing consisted of the transmit and receive phased arrays collinearly mounted within the same notional wedge structure that was used for the previous half-duplex testing. This housing was located on the roof of B-68, and connected to

the inboard FOT, HPA, and PC controller via interconnecting cables and waveguide, extending 175 feet from the roof down to the SESIF lab, as shown in figure 3.

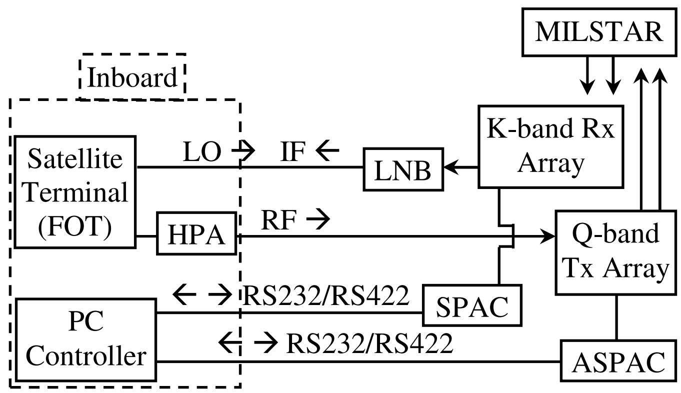


Figure 3: (U) Schematic of full-duplex static test setup

The Type 8 Mod 3 periscope antenna, which is a 5-¼" parabolic dish antenna, was used for the initial uplink and downlink acquisition and to provide the necessary control interface to the FOT. Without the Type 8 Mod 3 periscope antenna the FOT would enter a fault state during the satellite acquisition process due to the lack of feedback from the antenna. Once the initial uplink and downlink acquisitions were obtained, a remotely-actuated WR-22 electromechanical waveguide switch was activated, in order to reroute the amplified Q-band RF from the Type 8 input to the Q-band phased array input. A remotely-actuated coaxial switch was used to switch the FOT K-band downlink input from the Type 8 Mod 3 periscope antenna output to the K-band phased array output. A WR-22 waveguide coupler was incorporated in the waveguide junction box to attenuate the amplified Q-band RF signal from the HPA to the nominal operating input level of the transmit phased array (1.0 mW [0.0 dBm]). A waveguide coupler and broadband detector monitored the RF signal level at the input of the Q-band transmit phased array, to ensure proper input levels.

The pointing control of the phased arrays was managed via a PC laptop, running pointing software that had been developed using C++ (located in SESIF) communicating over RS-422 converters to the Q-Band Advanced System Phased Array Controller (ASPAC) and K-Band SPAC located on the roof of B-68 near the phased arrays.

For the full-duplex testing a manual peak-beam search, similar to that used for the half-duplex testing, was used to acquire the peak EHF downlink, by varying the phi and theta phased array pointing angles until a peak SNR was achieved. Due to their collinear mounting, the same pointing commands were used for both the K & Q band phased arrays. Both the MILSTAR and UFO satellites were used for this testing, based on availability. Using the Type 8 Mod 3 periscope antenna for uplink and downlink, a full-duplex Bit-Error-Rate (BER) link was established at which time the remotely actuated waveguide and coax switches were activated to convert to the uplink and downlink phased arrays. Testing was performed to obtain BER performance for various data rates, to determine the range of services supported by the transmit and receive phased array combination.

## FULL-DUPLEX STATIC TESTING RESULTS

The static testing consisted of varying full-duplex link data rates, in order to determine the limit of link robustness supported by the phased arrays. It was observed that data rates up to 64 kbps were reliably maintained with error-free BERs beyond $10^{-7}$. Using the Type 8 Mod 3 periscope antenna for the uplink and the K-band phased array for the downlink, a 128- kbps link with 0-bit errors was established; however, once the uplink was switched to the Q-band phased array, the link received bit errors with the BER falling to $10^{-4}$. Although this BER is not desirable for data and video it is acceptable for supporting voice links. This data rate limit was found to be a function of the small aperture area of the Q-band uplink phased array. As noted later herein, using the K-band phased array for the downlink and the Type 8 Mod 3 periscope antenna for the uplink, data rates of up to 512 kbps were established and reliably maintained.

Pointing offset testing was also conducted, in order to (a) observe the possible margin available in a particular link and (b) gain insight into the beam width of the transmit array. To support these trials, the downlink was switched to the periscope parabolic dish antenna while maintaining the uplink using the Q-band transmit phased array. It was observed that, with a 32 kbps downlink, bit errors began to appear at pointing offsets of $\pm$ 2° from boresight.

## FULL-DUPLEX DYNAMIC TESTING

The configuration for the full-duplex dynamic testing of the phased array system replicated that of the half-duplex dynamic testing: the notional wedge housing containing the phased arrays was integrated into the SSTM. The SSTM assembly was then base mounted to the six-axis motion table with the RF, power, control, and monitoring lines running down the length of the mast. Due to the inefficiency of running the Q-band RF signals on coaxial cables, flexible and rigid WR-22 waveguide sections were used to deliver the RF to the Q-band phased array input.

As described for the static condition, the power of the Q-band HPA output was attenuated to the Q-band phased array input power level of 1 mW (0 dBm). The method that had been employed during previous test scenarios was, again, used: the beam of the phased array was initially peaked using a manual peak-beam search. Once the optimal spherical array pointing angles were identified they were input into the pointing algorithm and motion table testing was performed.

For the full-duplex dynamic motion table testing the pointing software was completely rewritten using C++, such that it directly interfaced with the FOT in a configuration more realistic to a shipboard system. In order to determine the table position while under motion the Advanced Data Recording (ADR) data was extracted from the FOT and input directly into the pointing software in real time. This data was used by the PC controller to point the phased arrays. In addition to increasing the realism of the test scenario the revision of the pointing software also eliminated several unnecessary digital-analog and analog-digital conversions that existed in the legacy pointing configuration. Figure 4 shows the full-duplex dynamic test setup.

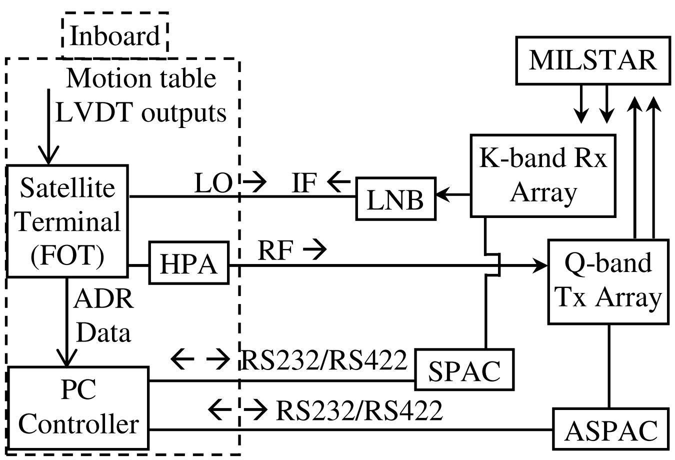


Figure 4: (U) Schematic of full-duplex dynamic test setup

## FULL-DUPLEX DYNAMIC TESTING RESULTS

The full-duplex dynamic test approach was the culmination of the previous half-duplex dynamic testing and full-duplex static testing, with the objectives being to re-establish and maintain the 64 kbps full-duplex data rate at the previously tested motion profiles.

The first step was to maintain a full-duplex LDR 2400-bps link with profile C at half rate ($\pm$ 10° pitch with a 25.0-second period and $\pm$ 20° roll with a 24.2-second period), which was achieved with an error-free BER approaching $10^{-5}$. When this same link was attempted with profile C at full rate ($\pm$ 10° pitch with a 12.5-second period and $\pm$ 20° roll with a 12.1-second period), it was not possible to achieve an error-free link. The determination was then made that the link could be established and maintained—error-free—when the Type 8 Mod 3 periscope antenna was used for the downlink and the Q-band phased array for the uplink. This finding indicates a possible latency issue with the downlink phased array controller and the need for a faster command link, in order to overcome the narrower downlink beamwidth of the K-band phased array. It was noted that, even during the periods when the link was incurring errors, the downlink phased array SNR remained constant at 30 dB. This detection explains why the latency issue was not detected during legacy half-duplex testing, as BER testing had not been performed. To compensate for this pointing latency the periods associated with the motion table profiles were increased, which effectively reduced the motion table profiles.

The next step was to establish a 64 kbps full-duplex Medium Data Rate (MDR) link and maintain it under motion; an error-free $10^{-7}$ BER was achieved with this link with profile C at half rate. Attempting profile C at ¾ rate ($\pm$ 10° pitch with a 16.7-second period and $\pm$ 20° roll with a 16.1-second period) resulted in bit errors. An error-free link was maintained, however, as expected, when the K-band downlink phased array was replaced with the Type 8 Mod 3 periscope.

Dynamic full-duplex testing at 64 kpbs was attempted with profile B, with error-free links achieving BERs of $10^{-6}$ at both the ¾ rate ($\pm$ 5° pitch with an 8.0-second period and $\pm$ 10° roll with a 16.1-second period) and full rate ($\pm$ 5° pitch with a 6.0-second period and $\pm$ 10° roll with a 12.1-second period). When attempting to reach a BER of $10^{-7}$ for profile B at both ¾ and full rates, however, BIT errors were experienced.

## FO LINK HALF-DUPLEX TESTING

A FO link prototype was designed and fabricated, to replace the coaxial cable used for RF signals as well as the copper data lines used for controlling the K-band downlink antenna. This link combines both the RF and control signals onto one single mode (SM) FO cable. The primary objective of this testing was to determine the feasibility of employing a FO link in an ongoing developmental phased array system.

Complications ensued when replacing the coaxial cable with a FO link because of the full-duplex RF signal

transmission that occurs in the coaxial cable. To reduce signal loss in the transmission line between the antenna and terminal, a low-noise block (LNB) down-converter is used at the antenna to down-convert the 20-GHz receive signal. Due to the hopping nature of the MILSTAR satellite signal, it is necessary that the local oscillator (LO) frequency needed for this down-conversion be transmitted from the terminal to the LNB. The LO signal is sent from the terminal using the same port on which the intermediate frequency (IF) is received, which requires a full-duplex link between the LNB (located at the antenna) and the terminal. This is easily accomplished when the signals are carried on a coaxial cable, but is more difficult when FOs are introduced. Due to the inherent differences between a FO transmitter laser and a FO receive diode their functions cannot be easily combined – especially at the high RF frequencies of interest in this case. When designing the FO link for this testing, therefore, various separation and isolation techniques were required, in order to combine two full-duplex channels (RF and control) onto a single FO cable. Both RF and optical circulators were used to separate and combine two-way signals, while wave division multiplexers (WDMs) were used to combine different wavelengths and provide isolation. While other methods of combining these signals onto a SM FO cable are available, this approach was pursued based on component availability and cost. The schematic of this test setup is shown in figure 5. The inboard and outboard sides of the FO link were connected via a 200-foot SM FO cable. Using this setup the K-band downlink was established, as previously described.

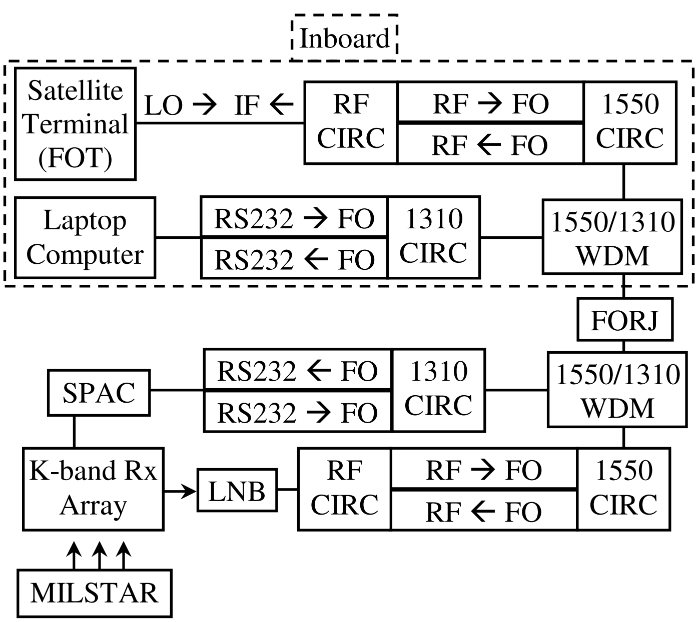


Figure 5: (U) Schematic of FO link test setup

After the RF signal portion of the FO link was established, a FO rotary joint (FORJ) electrical slip ring assembly was inserted into the FO path, as shown in figure 5. The addition of the FORJ had no effect on the SNR and resulted in less than a 2-dB reduction in noise floor power.

This FORJ-electrical slip ring assembly was custom built for this prototype. The assembly contained a single-channel SM FORJ, along with an integrated electrical slip ring assembly containing 12 slip rings. The slip ring has four twisted shielded pairs (TSPs) with a common ground, together with three power lines capable of 120 Vac at a 4-amp current. The intrinsic functionality of the slip ring assembly, although not used for this testing, will be in the future for the process of transferring power and control signals to the phased array across a rotary interface. This assembly is fluid-filled and pressure-compensated and, therefore, by design, capable of operating while being hydrostatically-pressure tested up to 1000 psi, without showing any signal degradation. Future plans utilizing the FORJ include hydrostatic-pressure, vibration and shock testing of the FORJ to determine its robustness.

The next setup of the FO link integration testing was conducted with the goal of introducing the RS-232 phased array control lines onto the FO cable that carried the RF signals. Using a FO modem, the RS232 control signals were converted to 1310-nm wavelength light and, based on their inherent full-duplex quality, sent through an optical circulator in order to combine them onto one FO cable. This 1310-nm wavelength light was then channeled through a 1310-1550-nm WDM, which multiplexed it with the 1550-nm wavelength light of the RF signals, thereby combining both RF and control signals onto a single FO cable.

## FO LINK HALF-DUPLEX TESTING RESULTS

The primary testing of the FO link was conducted by obtaining an uplink using a Type 8 Mod 3 EHF periscope antenna and the K-band phased array as the downlink, to perform BER tests at various data rates.

Using the FOT, the first attempt of an LDR data rate of 2.4 kbps was achieved with a $10^{-6}$ BER with no bit errors. Bit-error-rate- testing was continued with emphasis placed on maximum data rates over MDR links. The data rate was incrementally increased, with BER testing performed at each level.

A $10^{-8}$ BER with no bit errors was achieved for a 512-kbps link and was determined to be the threshold combination

of maximum achievable data rate with an acceptable amount of requested satellite resources. It is noted that, while a higher data rate could be achieved, it would require an unrealistic amount of satellite resources. The results of the BER testing are summarized in table 1.

Table 1: (U) Summary of FO Link Half-Duplex BER Test Results

| Data Rate | BER |
|---|---|
| LDR – 2.4 kbps | $10^{-6}$ |
| MDR – 2.4 kbps | $10^{-6}$ |
| MDR – 32 kbps | $10^{-6}$ |
| MDR – 64 kbps | $10^{-6}$ |
| MDR – 512 kbps | $10^{-8}$ |

The FO link testing performed was successful, and it verified that both the RF and control signals that are needed to control a phased array can be sent and received using a single FO cable. This testing also verified the use of a FORJ in conjunction with the single FO cable. In addition, BER testing of this FO circuit demonstrated that the FO link developed for this effort is robust, even at high data rates.

## CONCLUSIONS

Phased array testing was performed successfully using both half and full-duplex satellite links using the Q-band uplink and K-band downlink phased array antennas in conjunction with the FOT satellite terminal and the MILSTAR and UFO military satellites. Testing was performed successfully in both static and dynamic test configurations.

For dynamic testing the phased arrays were integrated into a notional housing atop the SSTM and tested under simulated ship motion using a six-axis motion table. Half-duplex testing was also performed using a FO link to carry both the control and RF signals for the downlink phased array on a single FO cable.

Legacy half-duplex dynamic testing had demonstrated the K-band narrowband phased array at TRL 6, as the testing was performed using a Navy SATCOM terminal while operating in a representative operational environment, integrated into the SSTM while under motion on the six-axis motion table.

Current full-duplex dynamic testing demonstrated the Q-band phased array at TRL 6 and demonstrated a full-duplex satellite link using only phased arrays, all within a relevant environment, using the MILSTAR and UFO military satellites, with the arrays integrated into the SSTM while under motion on the six-axis motion table. This testing also represents an iterative step towards integrating the array-pointing algorithm into the FOT satellite terminal.

The half-duplex FO link static testing demonstrated the feasibility of using a FO link to transmit both RF and control signals.

For full-duplex static testing various data rates were successfully demonstrated, with a maximum 64 kbps data rate achieved with zero-bit errors at a BER of $10^{-7}$ under good weather conditions.

The full-duplex dynamic testing, a culmination of the legacy half-duplex dynamic testing conducted in FY05 and the current full-duplex static testing, fulfilled its objective of re-establishing and maintaining the 64 kbps full-duplex data rate using the previously-tested motion profiles (B, C, and E). It was found that, in order to maintain an error-free link, it was necessary to reduce the speed of the motion profiles based on the possible latency issue [with the downlink phased array controller] and the need for a faster command link required to overcome the narrower K-band downlink phased array beam width.

Dynamic full-duplex link testing at a 64 kbps data rate was successfully performed at motion table profile B (both ¾ rate and full rate) with error-free links achieving BERs of $10^{-6}$. Dynamic full-duplex testing at a 64 kbps data rate was also successfully performed at motion table profile C (½ rate) with error-free links achieving BERs of $10^{-7}$.

For half-duplex static testing using the FO link, emphasis was placed on maximum data rates over MDR links. A $10^{-8}$ BER with no bit errors was achieved for a 512-kbps link. This was determined to be the threshold combination of maximum achievable data rate with an acceptable amount of requested satellite resources, given the aperture size of the K-band downlink phased array.